Planck 2015 Cosmology results

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Planck Collaboration

8th June 2015

Planck in 2015

- Parameters
  - Likelihood
  - Lensing
  - Dark Energy/Modified Gravity
- Inflation
  - Non-gaussianity
  - BKP
- (Geometry and Topology)
- (Isotropy and Statistics)

Where are we now with Planck?

- A refined analysis
  - Same "cross-spectrum" methodology for the C_l likelihood as in 2013
  - But less conservative now
    - More aggressive use of sky
    - Can present results using data from the full mission
- Redundancy
  - Multiple surveys per detector
    - Good for probing systematics
  - Multiple frequencies
    - Good for mitigating foregrounds

Main refinements since 2013

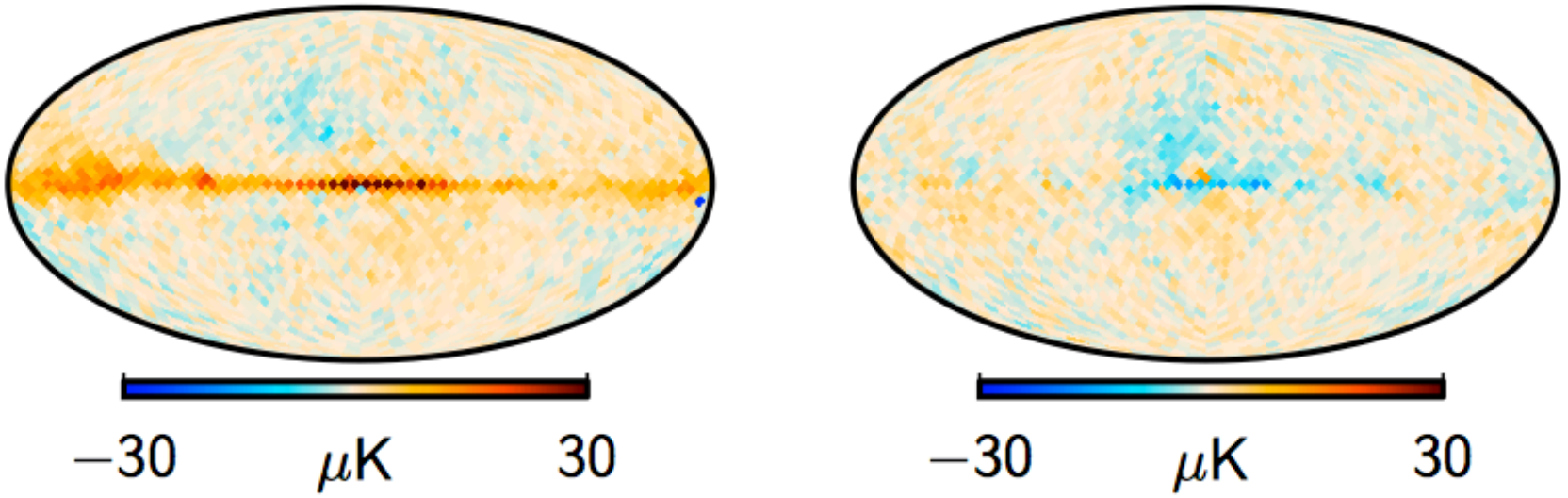
- Improved understanding of beams
  - Helped resolve calibration differences with WMAP
- Correction for the nonlinearity of the analogue-to-digital converters in the detectors
  - Removed much of the apparent gain variation seen in the 2013 data
  - Allowed us to calibrate properly off the orbital dipole

Planck Polarization

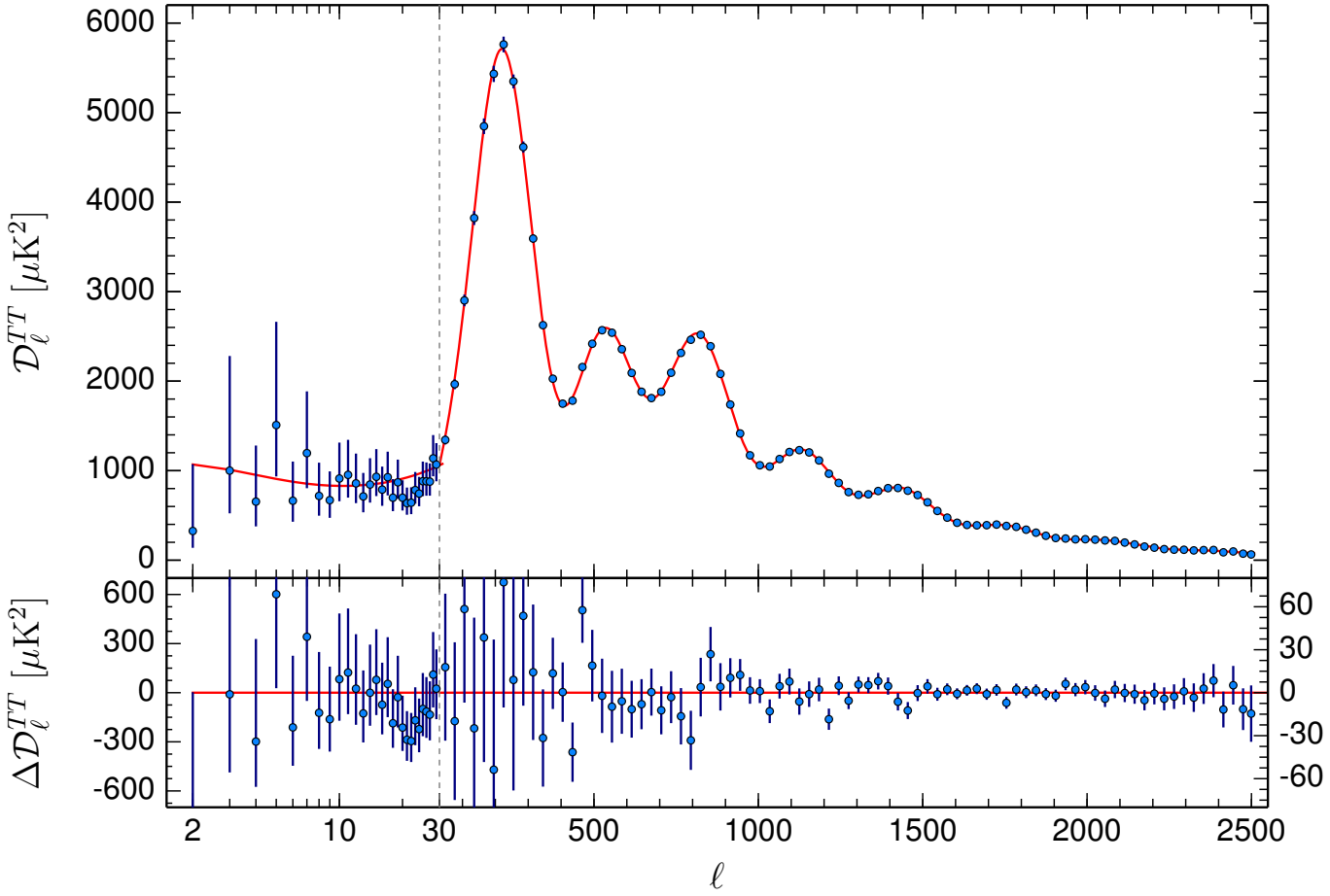
- What has P added?
  - Tighter error bars
  - Improvements in isocurvature constraints
  - Redundancy
    - Unresolved foregrounds in P are much less significant than in T
    - TE results are highly consistent with TT ones
- What complications has P bought?
  - T->P leakage (not fully quantified for 2015)

And at low-*l*

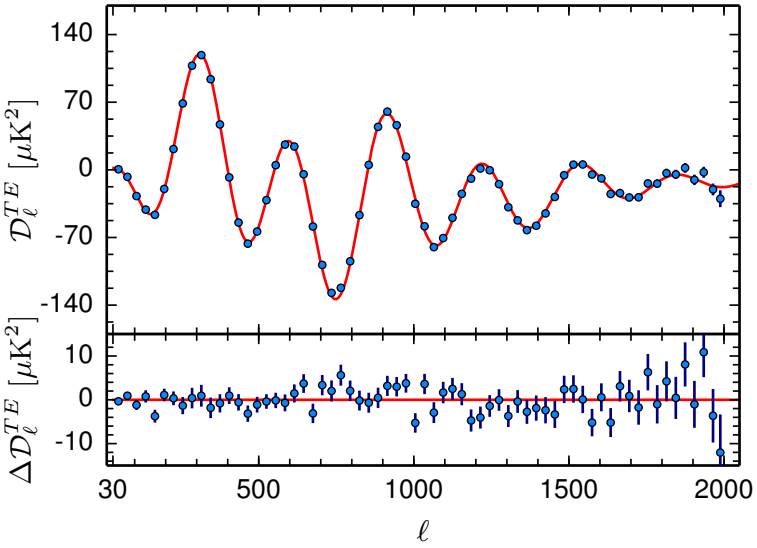
- We now use our own cleaned 70 GHz-based likelihood at low-*l*

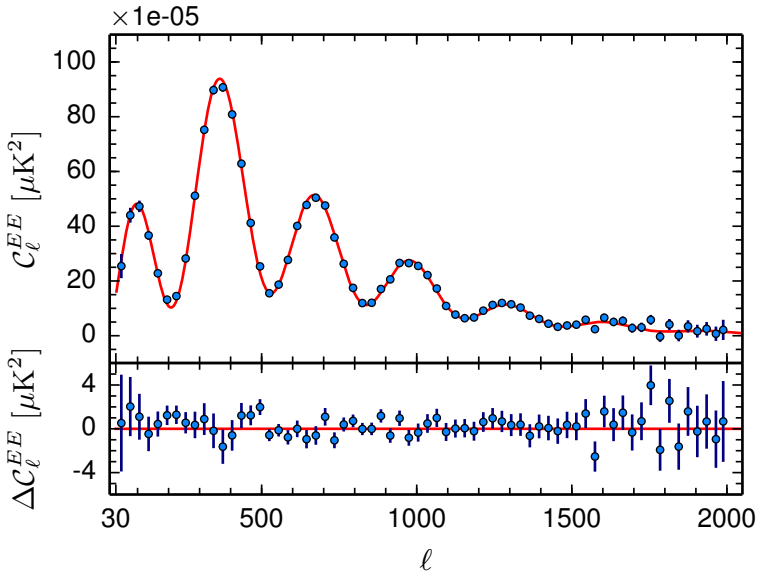


Our new “combined” TT

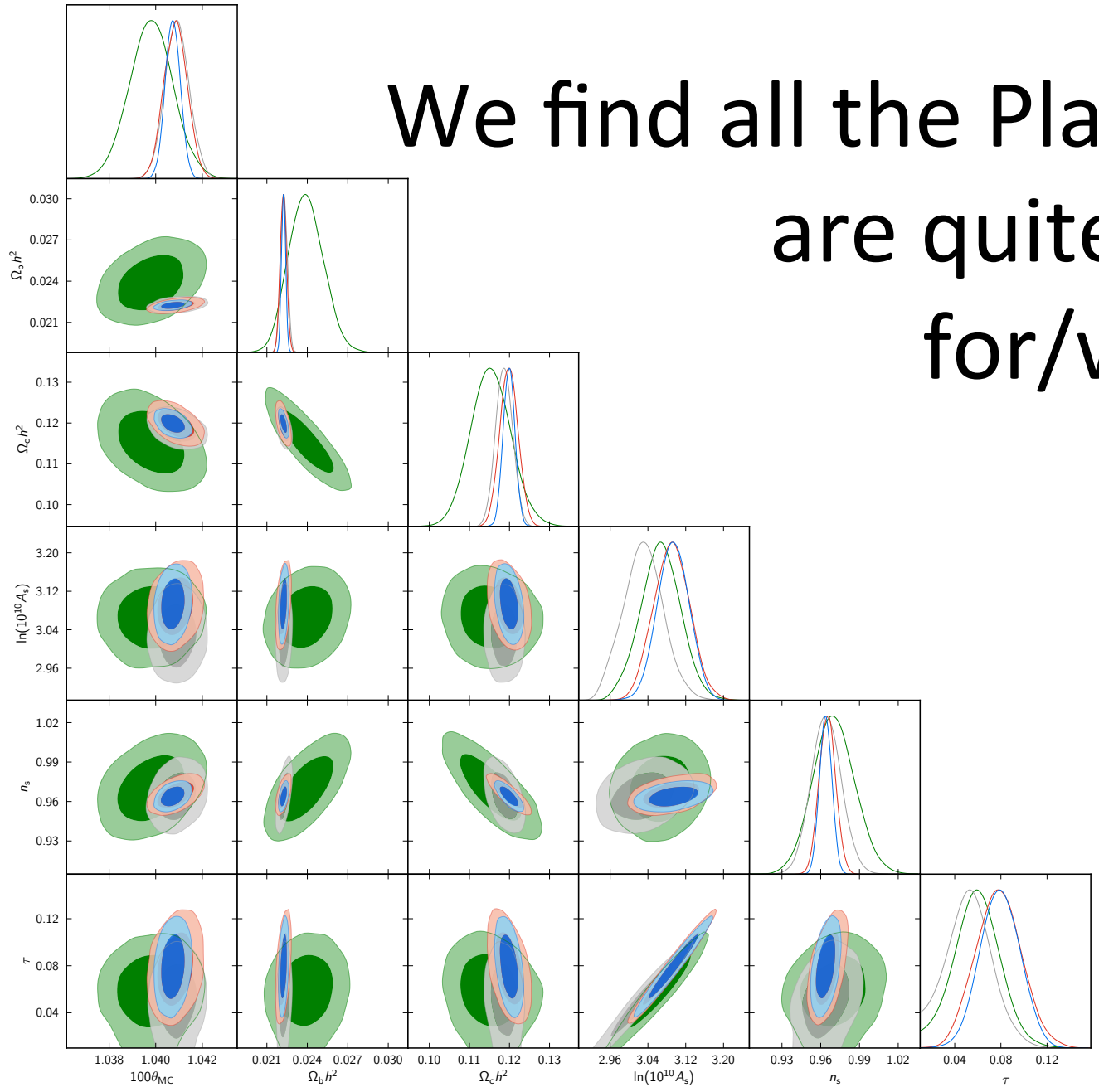


…and now our TE & EE:





We find all the Planck spectra are quite consistent for/with ΛCDM!



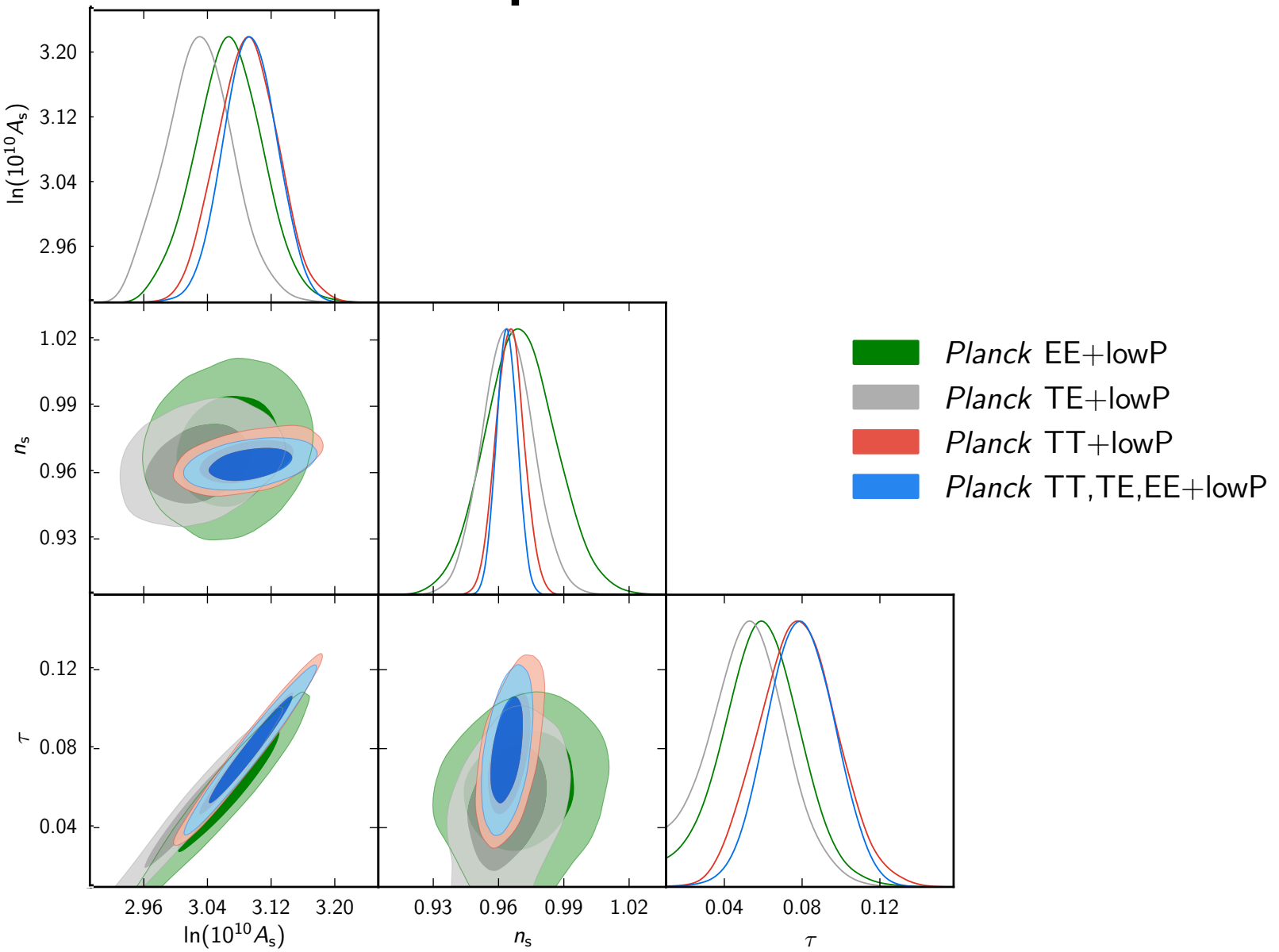
Planck EE+lowP

Planck TE+lowP

Planck TT+lowP

Planck TT,TE,EE+lowP

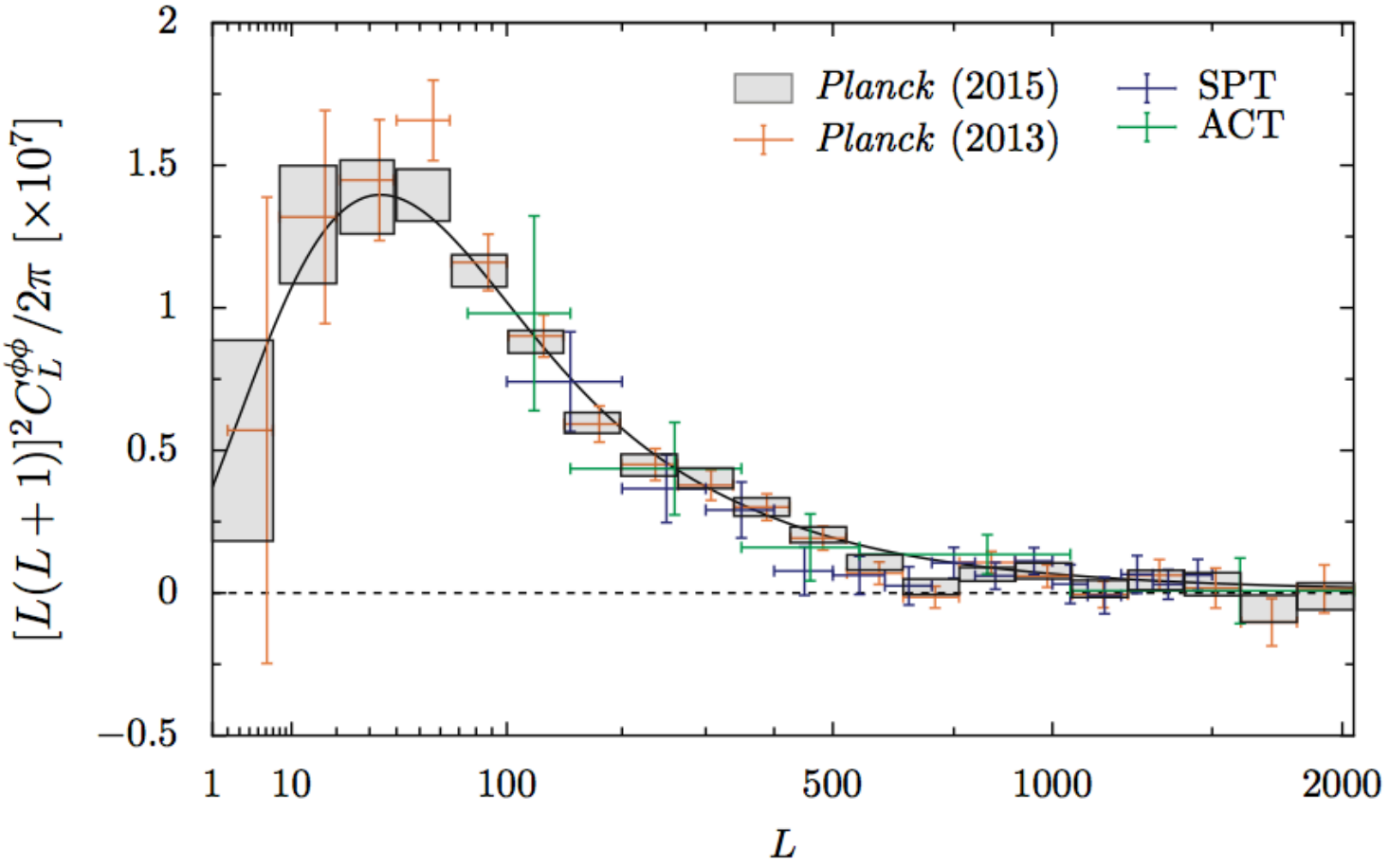
An Example Zoom:



Planck Lensing

- Mass inhomogeneities deflect the CMB photons on their way to us
- Can calculate the power spectrum of the deflection field and compare it to theory
  - i.e. a four-point function of the CMB
  - Mostly sensitive to matter nearby so can be thought of as an internal “low-redshift” dataset
  - Helps break degeneracies
- New for 2015 is the inclusion of polarization maps in the inference

2015 Lensing potential spectrum



Extensions

- Ω_k
  - TT: -0.052 ± 0.05 (95%)
  - TTTEEE: -0.040 ± 0.04 (95%)
  - TTTEEE+lensing: -0.004 ± 0.015 (95%)

- $dn_s / d\ln k$
  - TT: -0.008 ± 0.016 (95%)
  - TTTEEE: -0.006 ± 0.014 (95%)
  - TTTEEE+lensing: -0.002 ± 0.013 (95%)

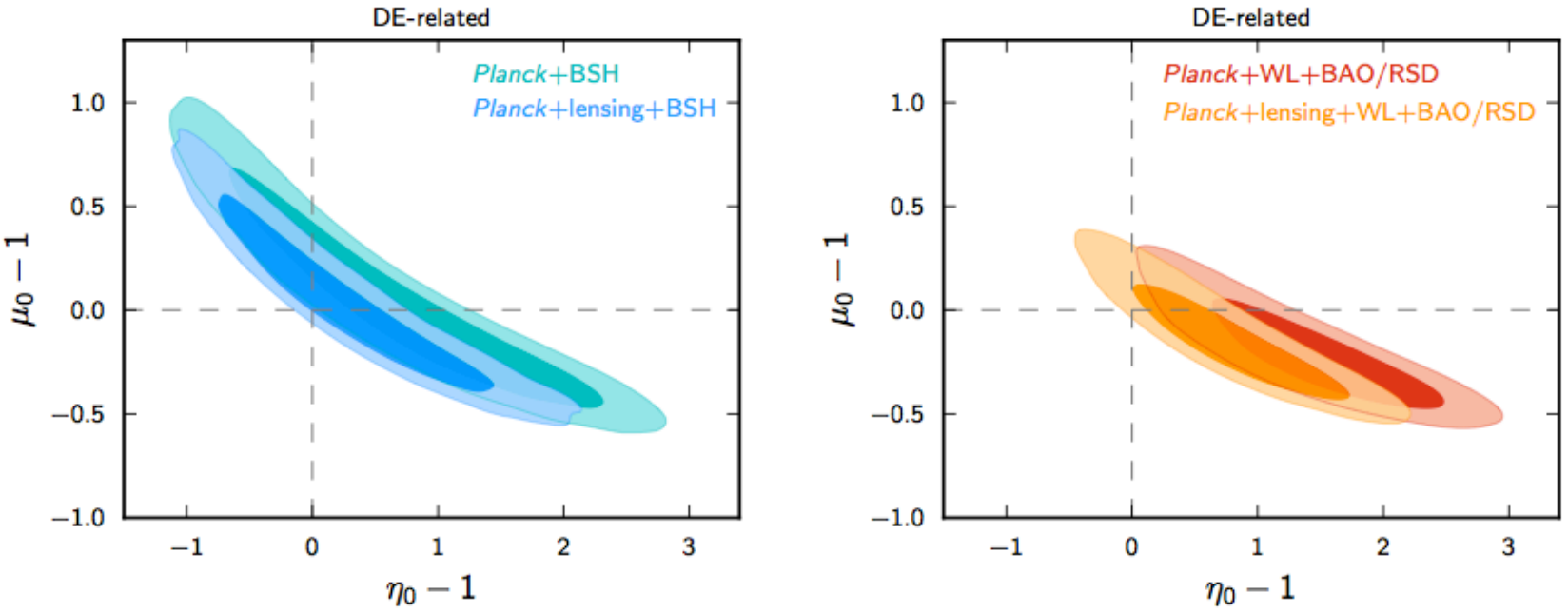
So, the parameters bottom line:

- Power spectra are highly consistent with the flat ΛCDM model
  - Minor tension with curvature with Planck alone
- The varying analyses themselves are highly consistent within flat ΛCDM

Dark Energy/Modified Gravity

- Meaningful constraints typically need additional low-redshift data over that needed for our ΛDM analyses
  - Any modifications that only affect the background are *not* favoured over ΛCDM
  - Modifications affecting the perturbations also can be found that are favoured at 2-3 σ depending on the choice of dataset
    - Go away when Planck lensing is used…

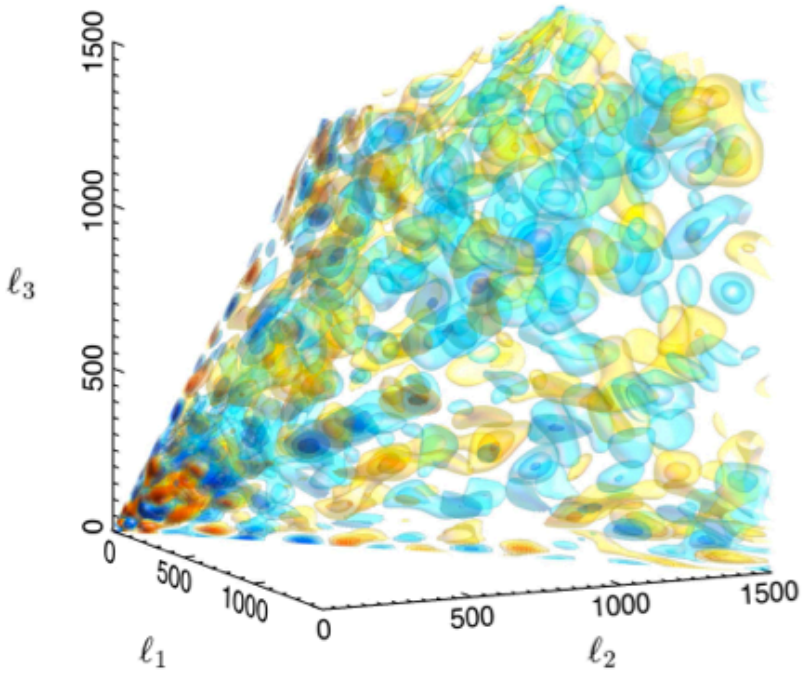
E.g. affecting the Poisson equation and no anisotropic stress condition…



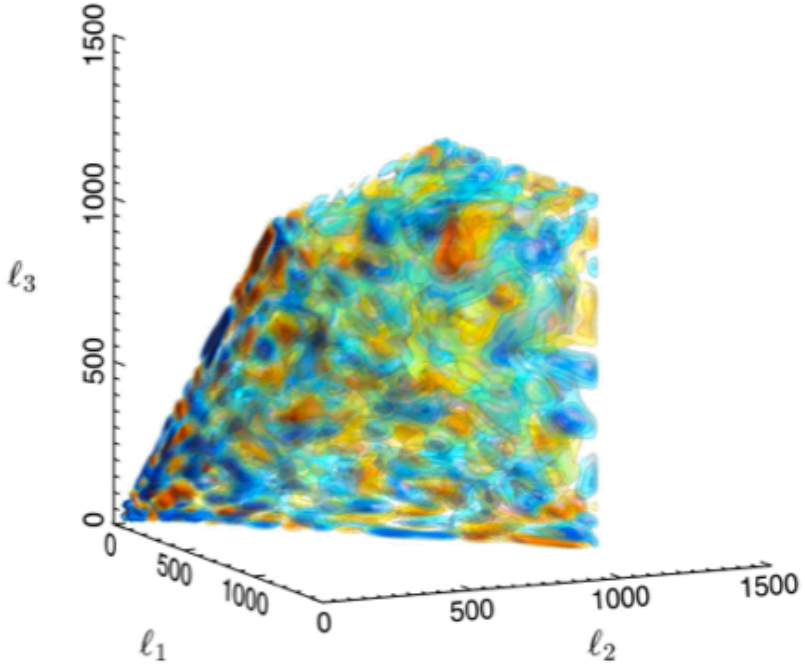
Non-gaussianity

- Lensing gives a specific, non-gaussian, signature
- One can search more generally for non-gaussianities in the CMB
  - Various estimators, now in 2015 also including E
- No convincing detections made
  - Again consistent with ΛCDM

TTT



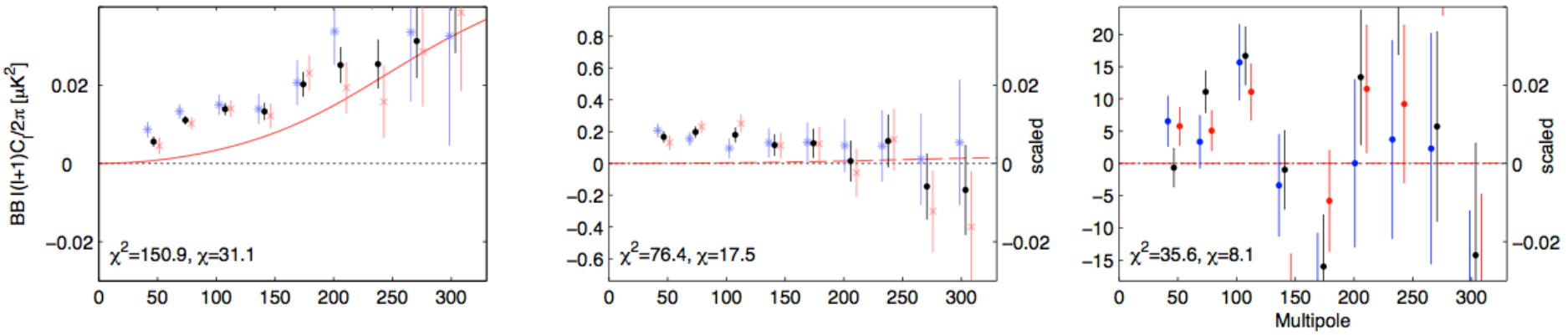
EEE



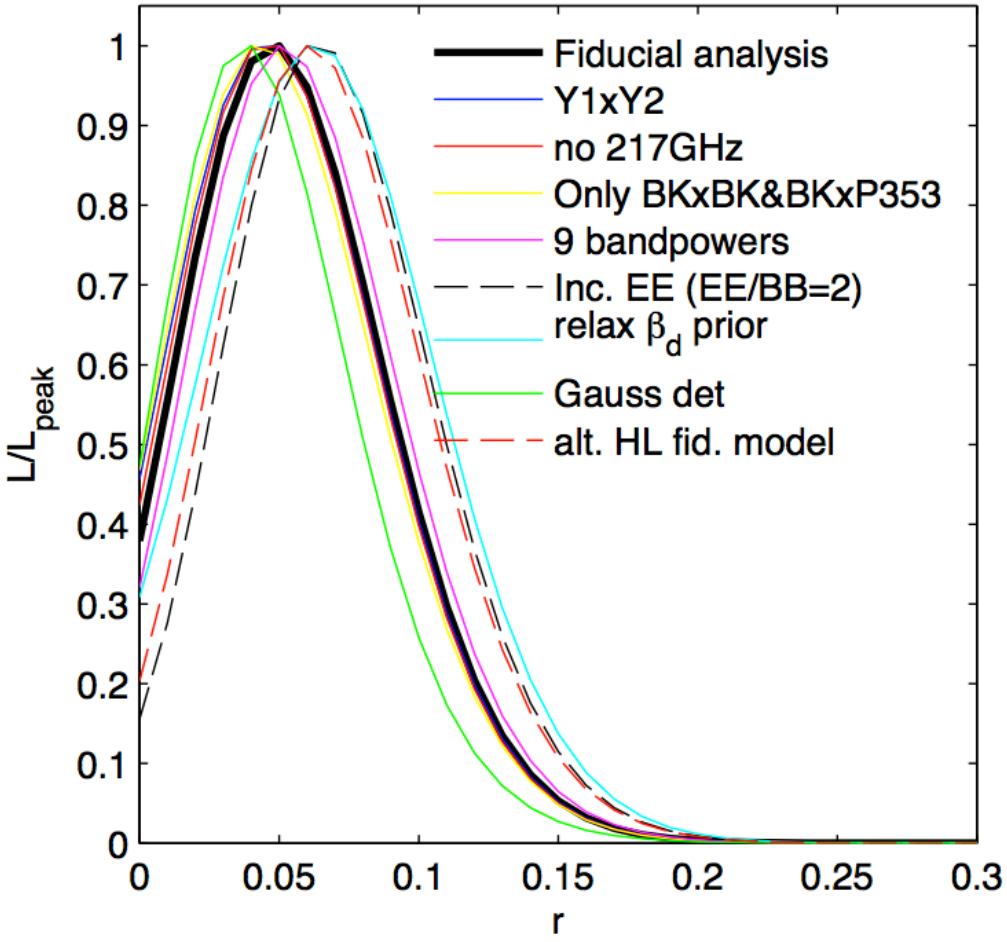
BICEP2/Keck Array and Planck

- Planck added the 353 GHz polarization maps
  - Useful as a dust tracer
    - Dust has a different emission spectrum to the black-body CMB and is brighter at higher frequencies
  - Multiply by 0.04 to get it down to BK's 150 GHz
    - 353x353 spectrum is still very noisy even now
      - Suggests there is something there though
    - But the BKx353 spectrum is helpful
  - One then constructs a likelihood out of
    - BKxBK, BKx353 and 353x353

The spectra


BB l(l+1)C_l/2π [μK^2]
0.02
0
−0.02
χ^2=150.9, χ=31.1
0
50
100
150
200
250
300
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
χ^2=76.4, χ=17.5
scaled
20
15
10
5
0
−5
−10
−15
χ^2=35.6, χ=8.1
Multipole

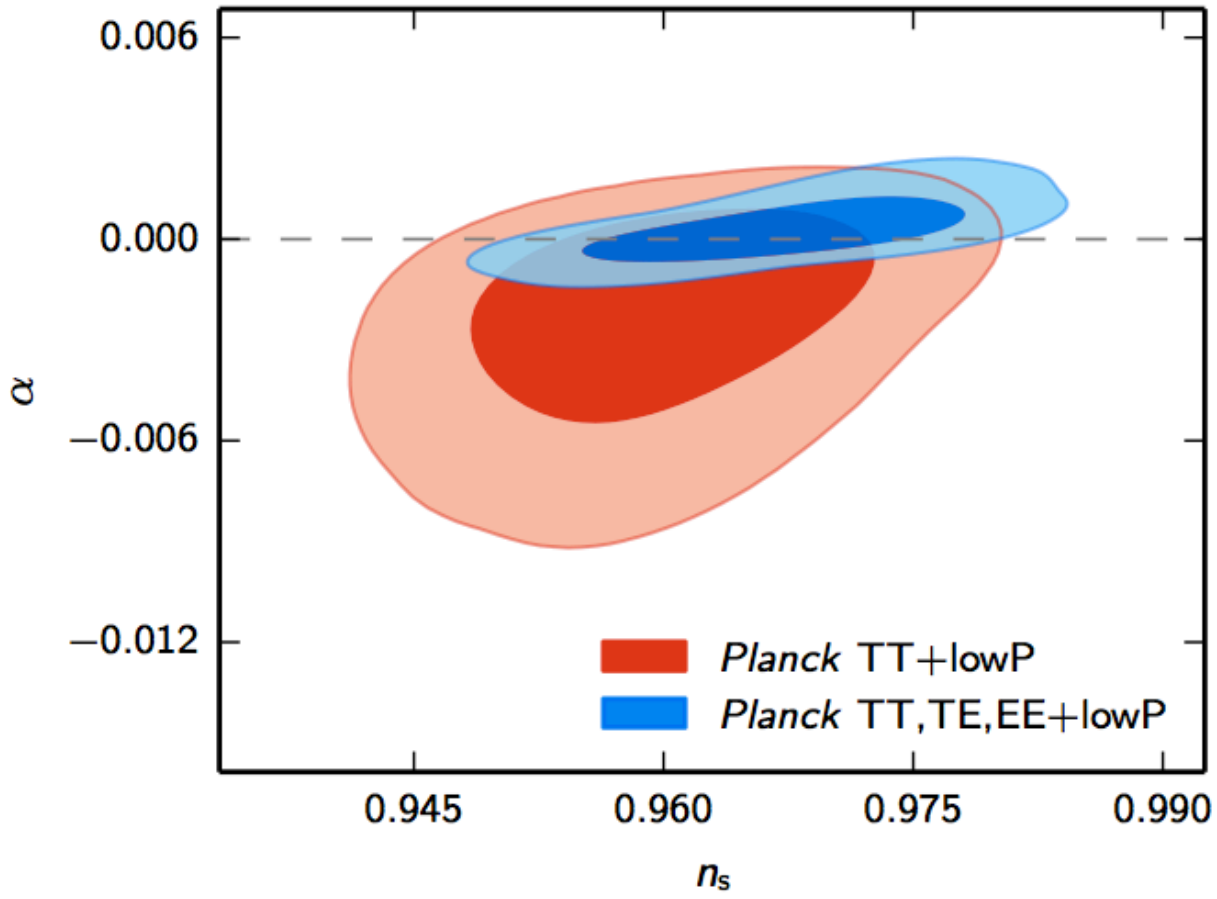
Illustrative *r* posteriors…



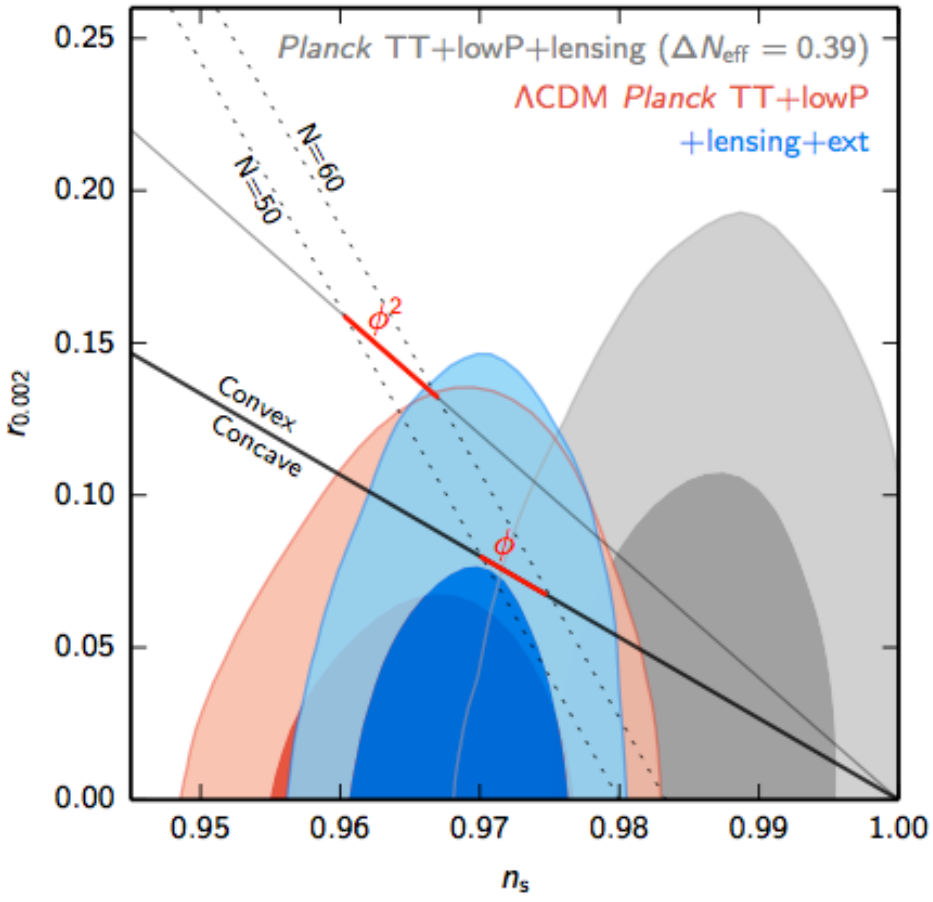
Inflation

- Adiabaticity of the perturbations
- Implications of n_s & r constraints for inflation
- (Reconstruction of the primordial power spectrum)

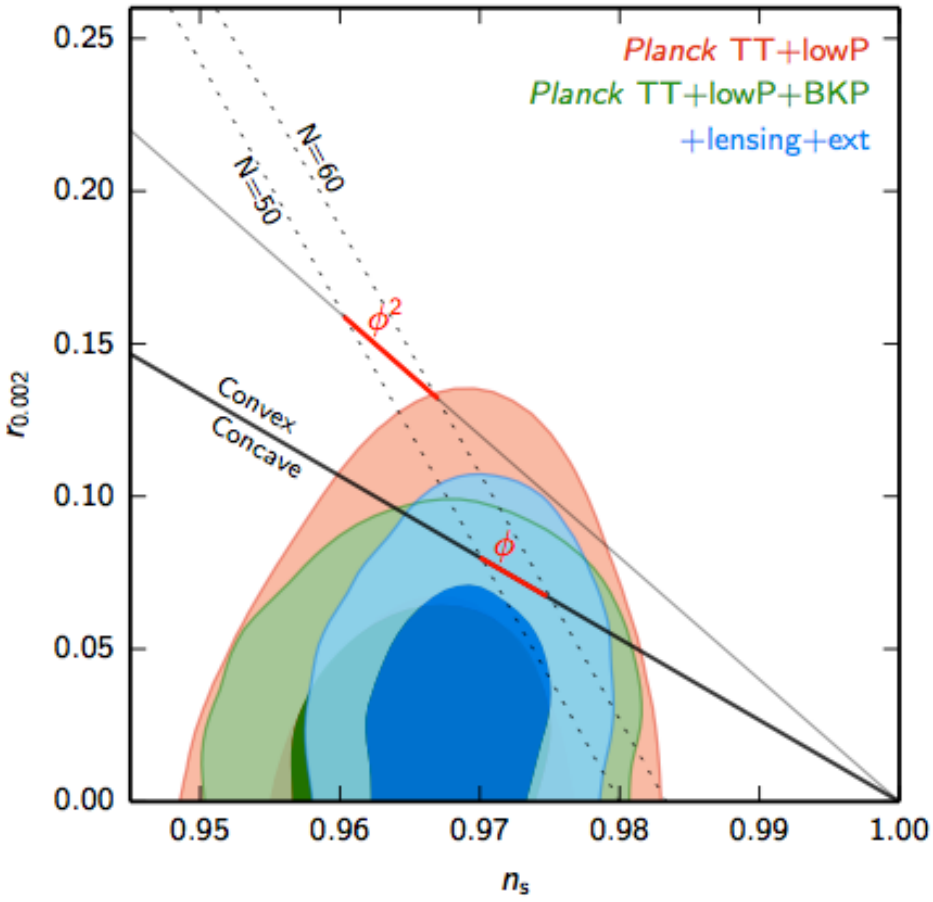
Perturbations are consistent with being adiabatic…



Inflation: Planck n_s vs r



Inflation: Planck+BKP n_s vs r



What is still to come from Planck?

- 2015
  - Likelihood paper
  - Likelihood
  - 100, 143 & 217 polarization maps
  - Low-ell paper
- 2016
  - Analysis with Improved Timeline Processing

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada.

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

What does it mean?

- Flat ΛCDM works *really well*
- Inflation?
  - Results are highly consistent with "*single field with a flat potential*" inflation
    - How generic are such models in string theory?
    - Then, if such inflation is possible, is it *probable*?
  - BKP *doesn't rule out* a significant tensor contribution to the fluctuations

What is still needed from theory?

- Well-motivated models that make subtle, distinctive and correlated predictions
  - A dip at *l*=25 *and* {another effect} anybody?
- Alternatives to inflation

- Better understandings of measures on cosmological physics and histories

Thanks!